Cooling Accelerator Beams

Eduard Pozdeyev
Collider-Accelerator Department

BROOKHAVEN
NATIONAL LABORATORY

- **Introduction**
- Stochastic cooling
- Coherent electron cooling
- Electron cooling

Introduction

- Cooling decreases the beam phase-space volume (without loosing particles) and therefore increases the phase-space density.
- Cooling reduces the transverse emittance and the rms energy spread of the beam. This causes beam sizes to shrink.

Why is cooling needed:

1. Preservation of beam quality
2. Improvement of luminosity (collision rates) and resolution
3. Accumulation of rare particles

Introduction

Collision rate $\dot{n}_c = \sigma L$

Luminosity $L = \dfrac{N_i^2 f_c}{4\pi\varepsilon\beta^*} F\left(\dfrac{\beta^*}{\sigma_z}, L_d\right), \quad 0 < F < 1$

Coefficient *F* takes into account the hour-glass effect and the finite length of the detector vertex region

L_d – vertex length

β^* – beta func.@ IP

ε – emittance

σ_z – bunch length

N_i – ions/bunch

f_c – collision freq.

(i) Beam-Beam collisions, (ii) Intra-Beam scattering, (iii) noise in accelerator systems increase the beam phase-space volume (and dimensions) and enhance particle losses. These effects cause luminosity degradation.

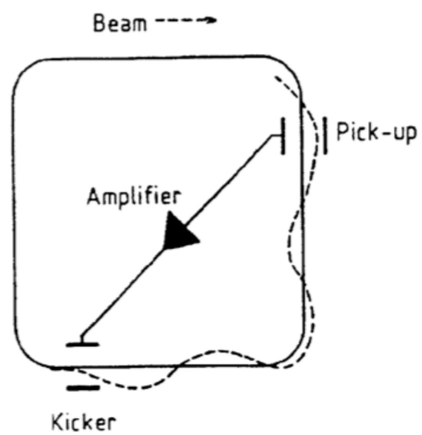
To increase integrated luminosity one has to reduce or preserve emittance and energy spread:

- Reduced transverse size at collision point
- Reduced longitudinal beam size
- Reduced losses and extended luminosity lifetime -> increased integrated luminosity

- Why to cool accelerator beams
- **Stochastic cooling**
- Coherent electron cooling
- Electron cooling

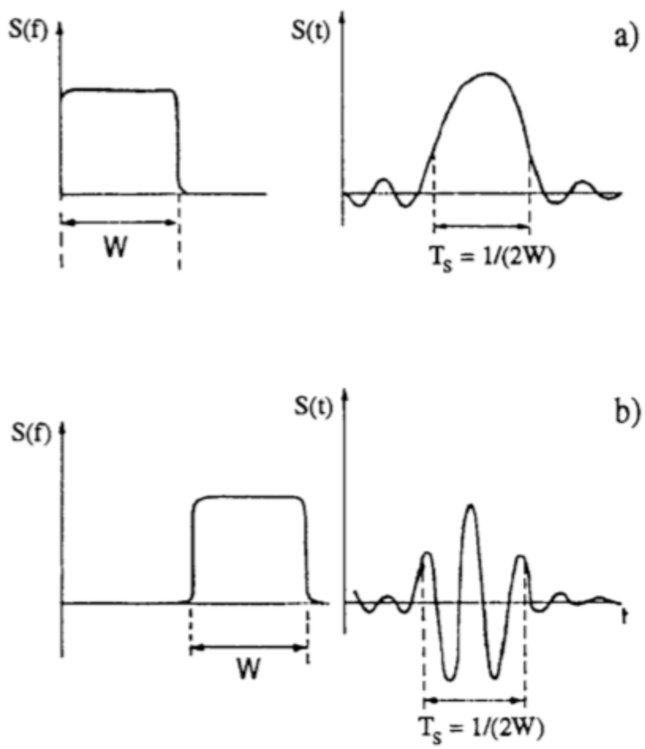
Invented by Simon van der Meer. First used at CERN SPS. Nobel prize in Physics in 1984 (shared with Carlo Rubbia).

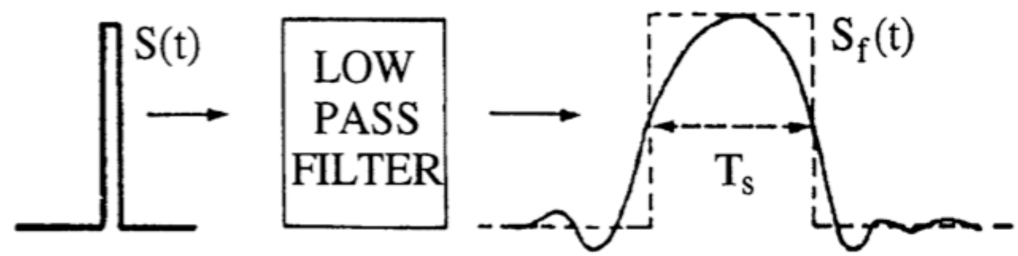
Stochastic cooling – general picture



Typical stochastic cooling scheme consists of pickup, amplifier, and kicker.

Correlation between length and bandwidth



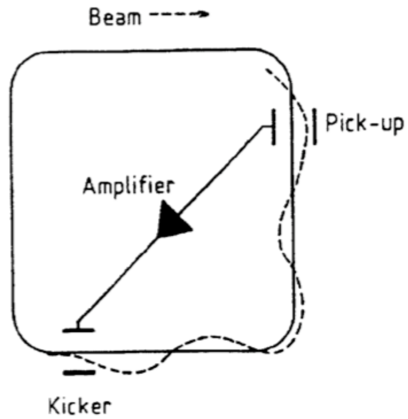


A delta-function signal produces a pulse of length T_s=1/(2W) after passing through the amplifier with with a bandwidth of W.

Thus, a particle feels a combined kick of particles in a beam slice with a length of T_s. The number of particles per slice:

$$N_s = \frac{N}{T_b} T_s = \frac{N}{T_b} \frac{1}{2W}$$

Stochastic cooling - general picture



1) $$\tilde{x} = x - \frac{g}{N_S}\sum_S x_i$$

2) $$\Delta(x^2) = -2gx \cdot \langle x \rangle_S + g^2\left(\langle x \rangle_S\right)^2$$

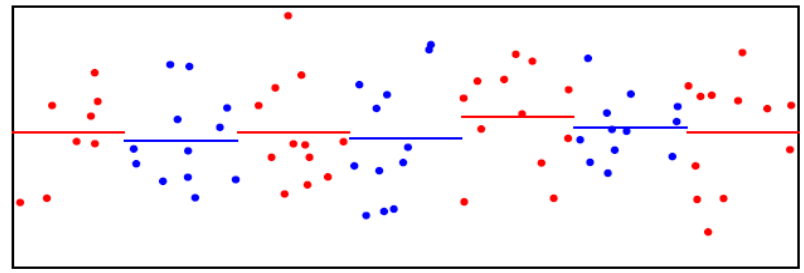
3) $$\left\langle \Delta(x^2) \right\rangle_S = -2g\left(\langle x \rangle_S\right)^2 + g^2\left(\langle x \rangle_S\right)^2$$

4) $$\left\langle \Delta(x^2) \right\rangle_S -> \Delta\left(x_{rms}^2\right), \quad \left(\langle x \rangle_S\right)^2 -> x_{rms}^2 / N_S$$

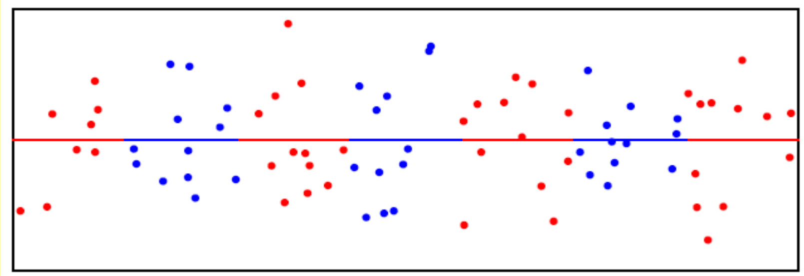
5) $$\Delta\left(x_{rms}^2\right) = -\frac{2g - g^2}{N_S} x_{rms}^2$$

6) $$\frac{dx_{rms}^2}{dt} = -\frac{2g - g^2}{T_0 N_S} x_{rms}^2 = -\frac{2Wl_b}{NC}(2g - g^2)x_{rms}^2$$

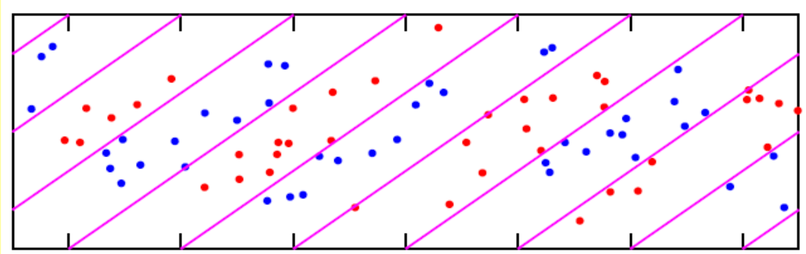
before kicker



after kicker



after mixing



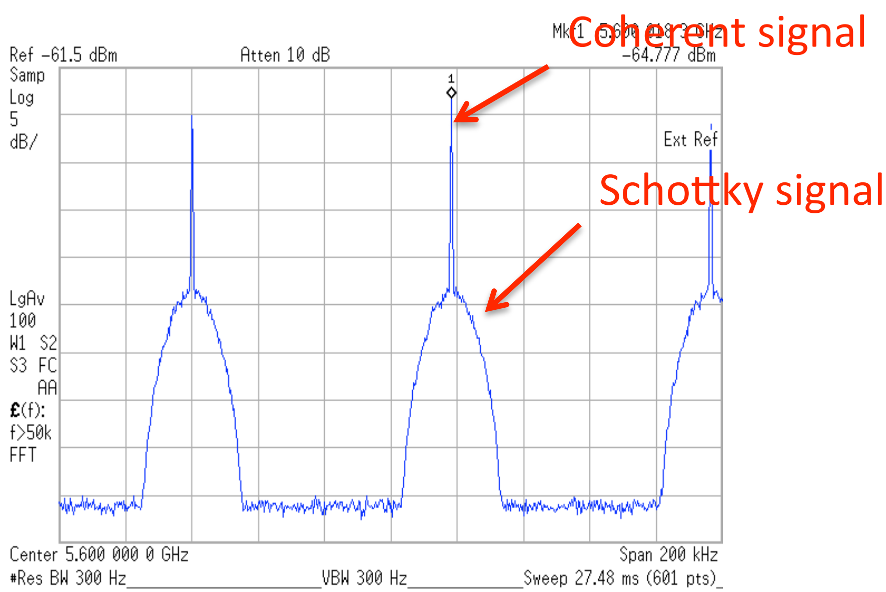
Mixing randomizes distribution of slices

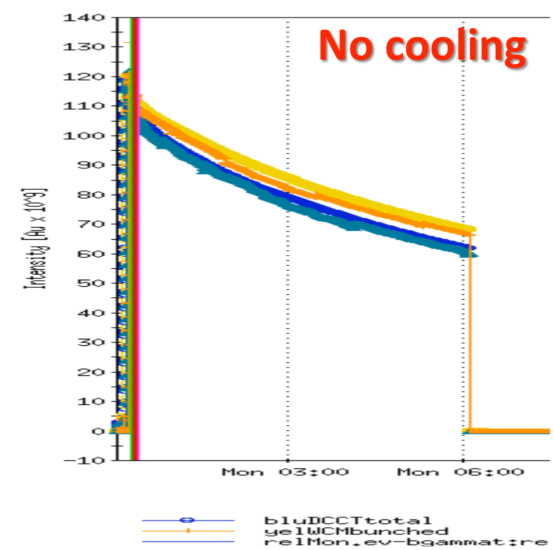
Momentum (energy) stochastic cooling at RHIC

1. At RHIC we want to counteract IBS during stores to reduce beam dimensions and increase integrated luminosity
2. Prevent de-bunching and particle losses (halo cooling)

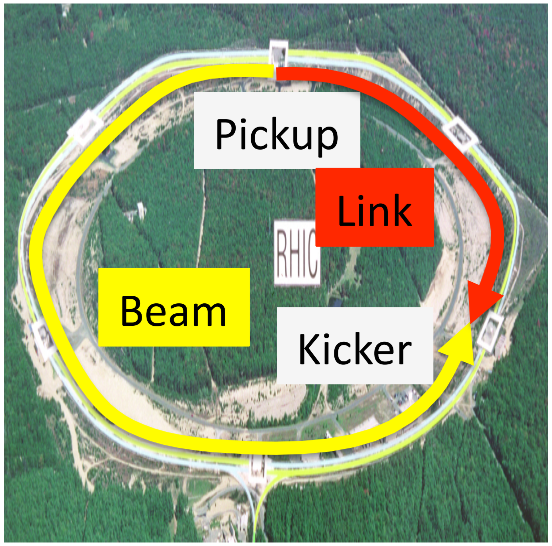
The challenges for RHIC S.C. are:

1. A cooling time of about 1 hour is required.
2. Beam energy is 100 GeV/nucleon. Strong kickers broadband (3 GHz) are required.
3. **The beam is bunched to 5 ns in 200 MHz rf buckets. Strong coherent signal**

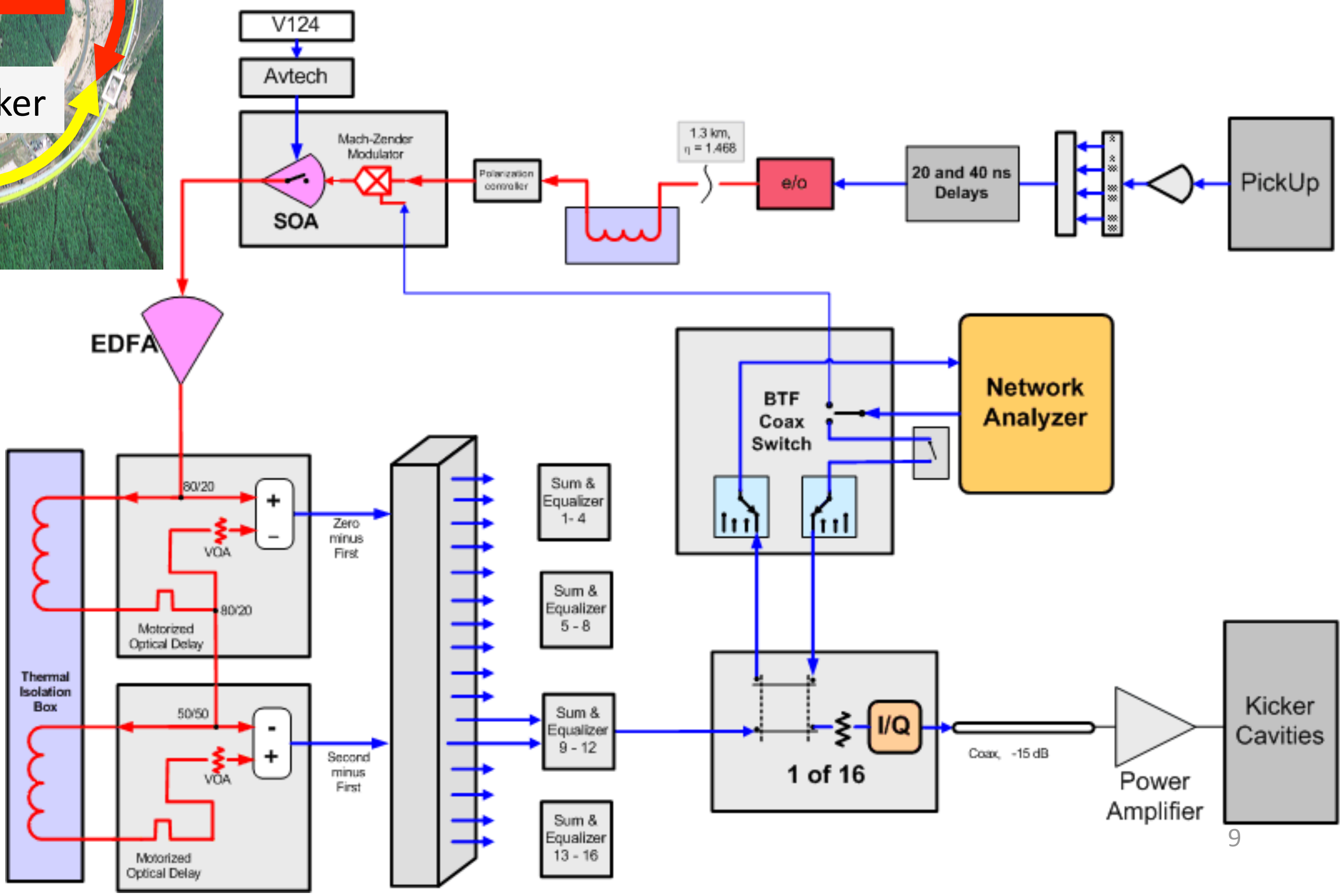




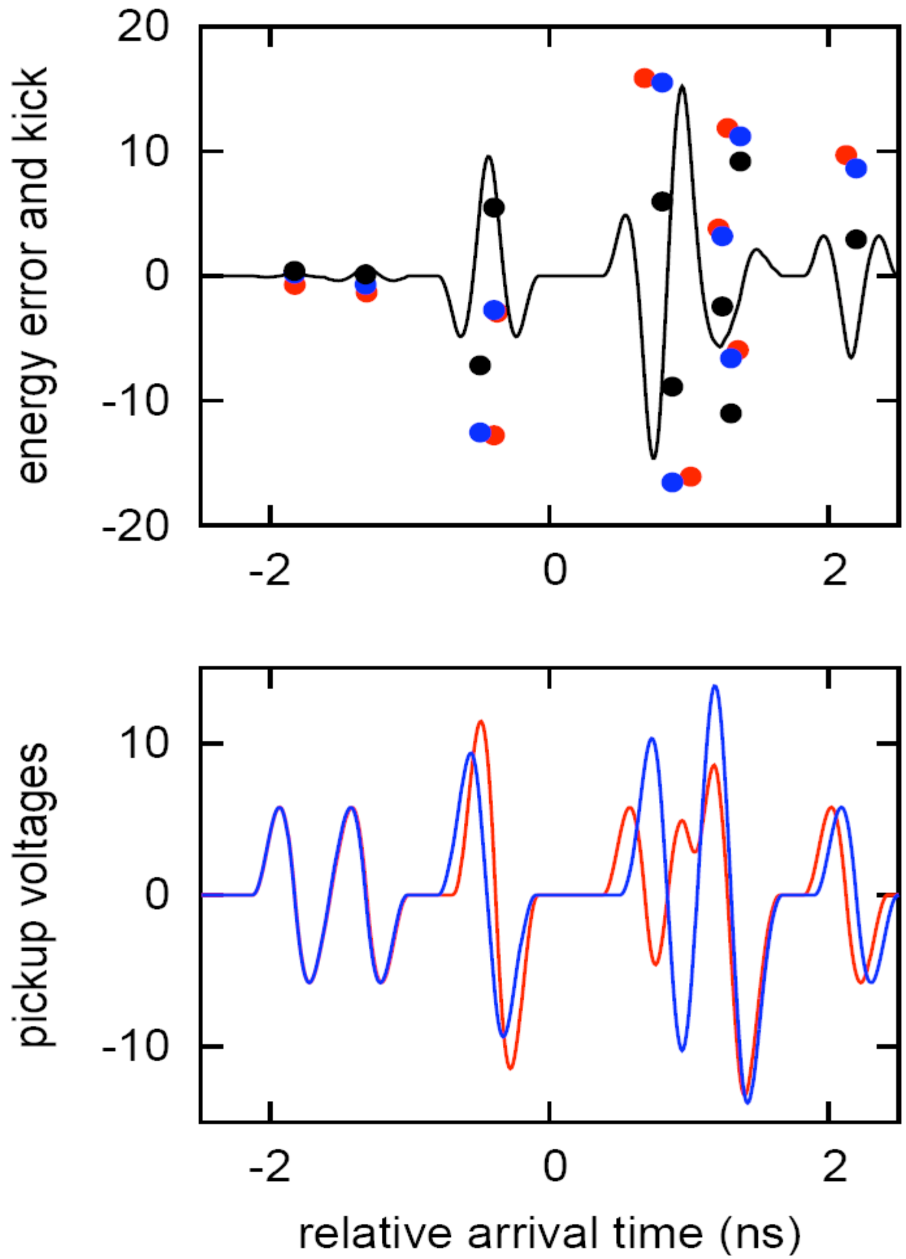
Stochastic momentum cooling at RHIC



Stochastic Cooling Low Level Block Diagram



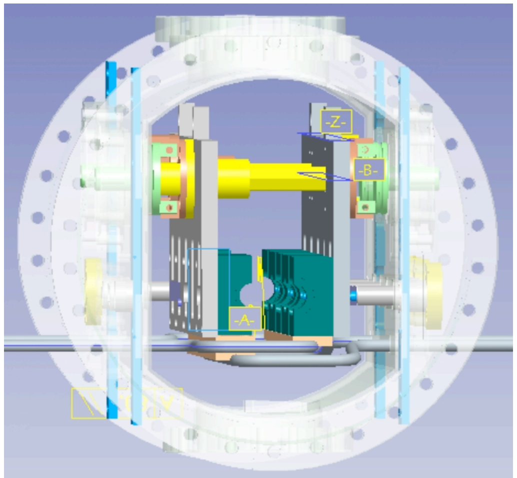
Momentum cooling simulations

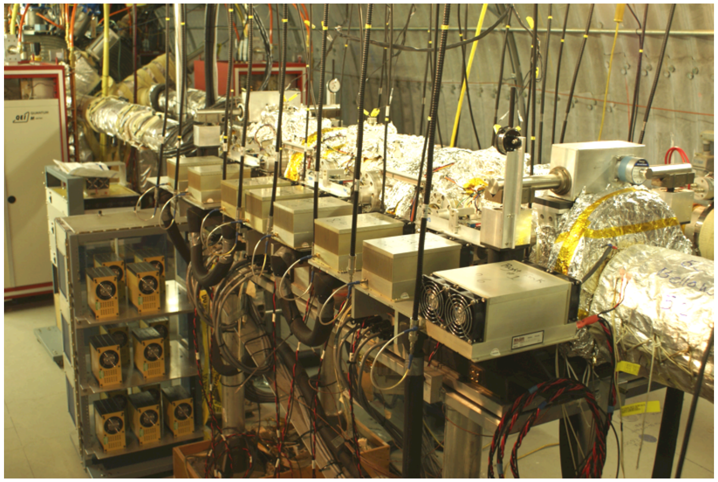


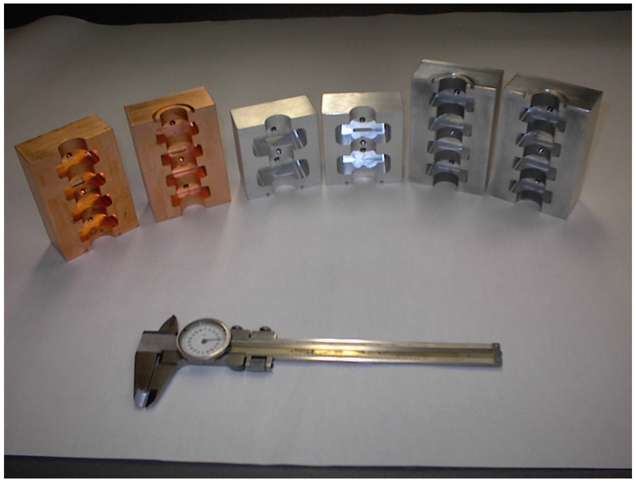
Red – 1st turn
Blue – 2nd turn
Black – after kick

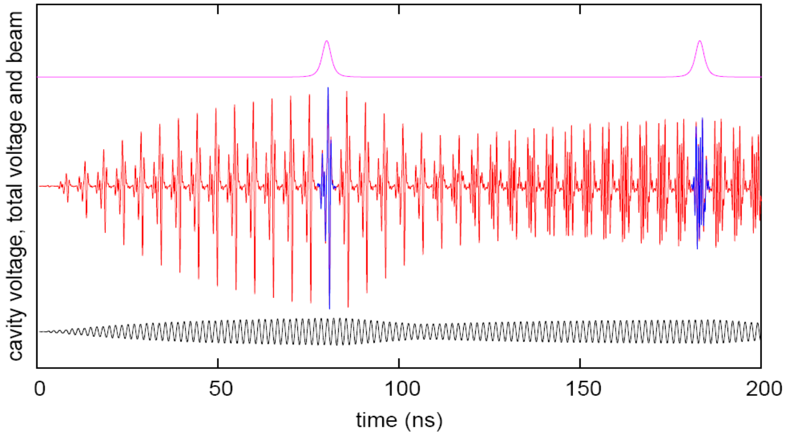
Kicker cavities

- A lot of punch at broadband (5-8 GHz) is needed
- Use several (16) cavities with relatively high Q (~800). Each cavity has different resonant frequency. The Q is defined by the distance between bunches and the cavity frequency.



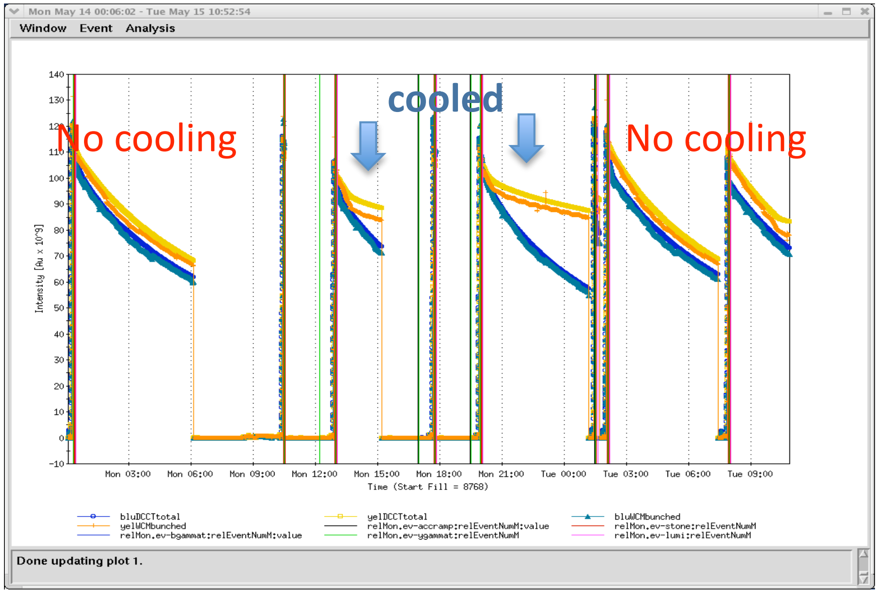




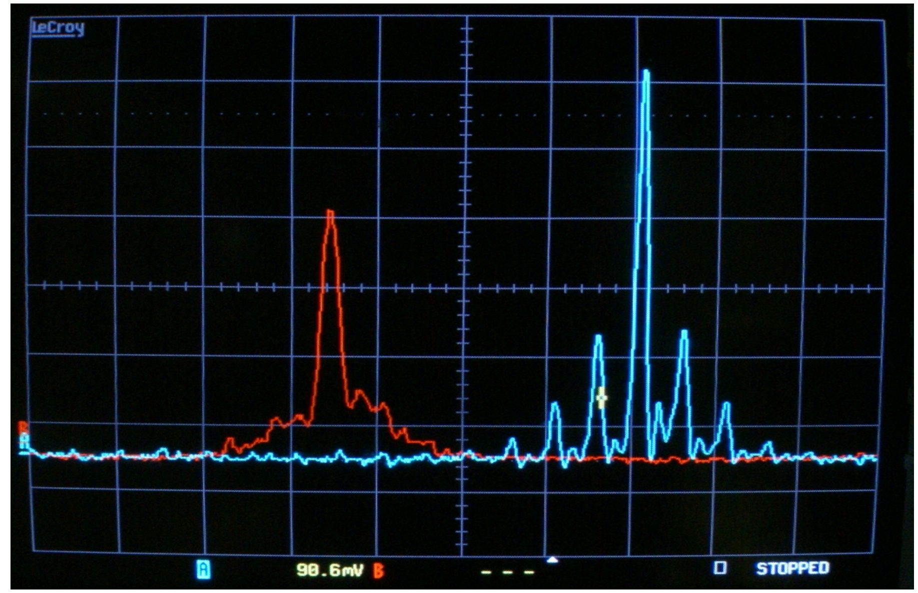


RHIC stochastic cooling results

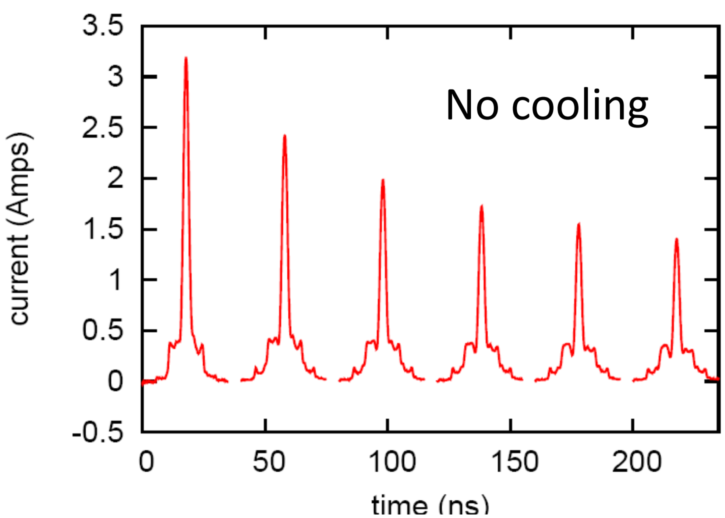
Life time increases

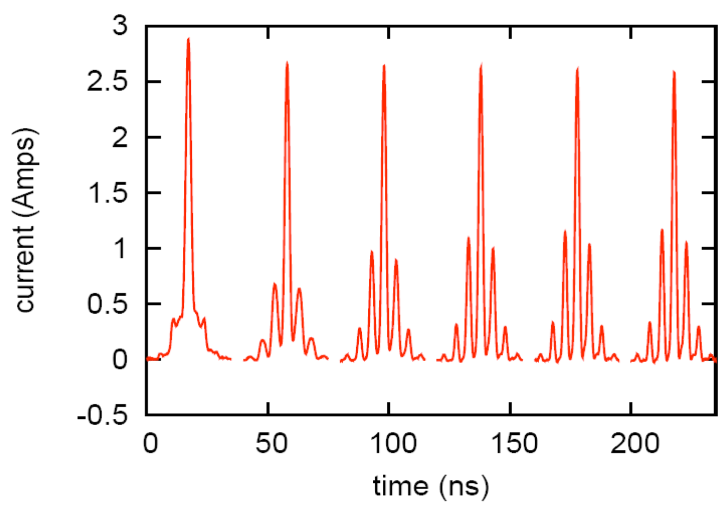


Peak current increases



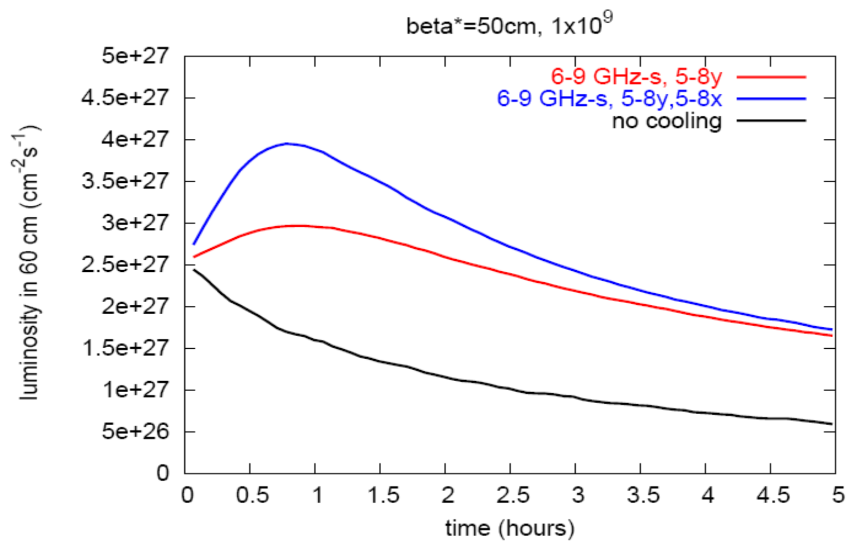
Measured evolution of a bunch over 5 hour store, without and with cooling





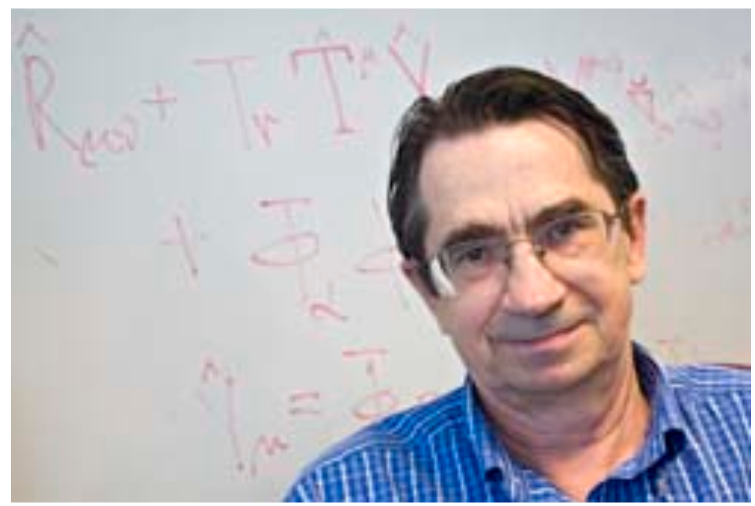
Plans for RHIC stochastic cooling

- Install and test transverse (two planes, one ring) this year
- Make blue momentum cooling operational next year
- Use direct RF links for transverse instead of optical fiber links
- Increase frequency of amplifiers
- If transverse cooling test is success, install transverse cooling in the other ring
- Planned increase of integrated Au luminosity is factor 4. (Stochastic cooling cannot cool protons. Too many particles per slice.)



- Why to cool accelerator beams
- Stochastic cooling
- **Coherent electron cooling**
- Electron cooling

Proposed by Ya. (Slava) Derbenev about 30 years ago in Novosibirsk (same guy who proposed a “Siberian snake” together with Kondratenko).

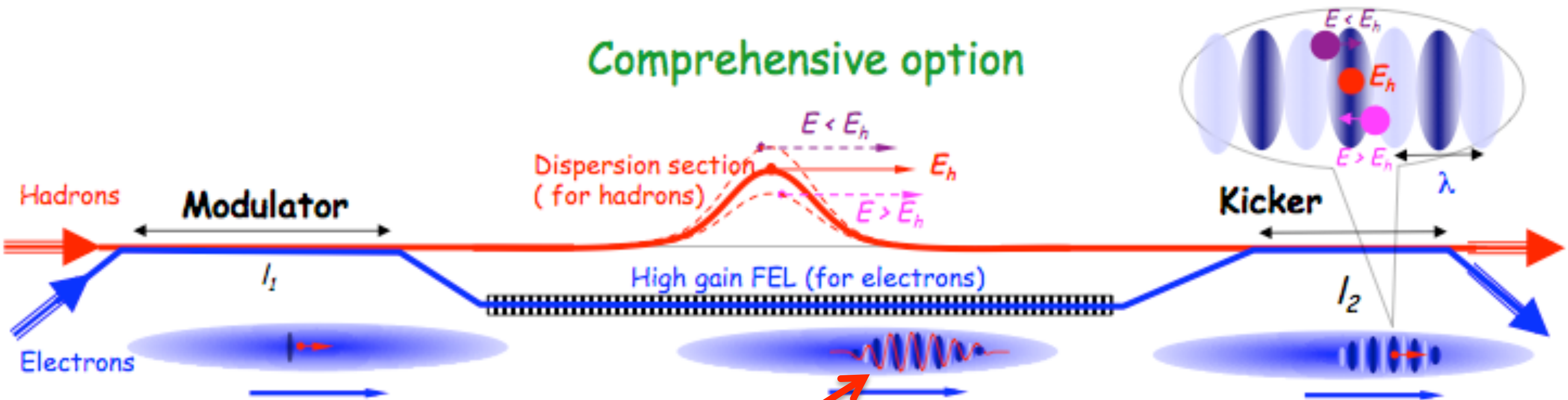


Coherent Electron Cooling (CEC)

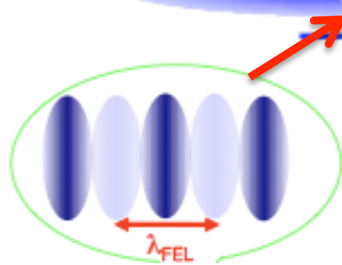
- CEC is, in principle, stochastic cooling
- Electron beam used to transfer information
- Similar to stochastic cooling CEC consists of
  - Pickup (or modulator): ions imprint themselves in electron beam
  - Amplifier: the perturbation of e-beam created by the ion beam is amplified (for example, an FEL)
  - Time-of-flight dispersion section: ions are separated longitudinally according to their energy
  - Kicker: the amplified perturbation of e-beam is applied back to the ions

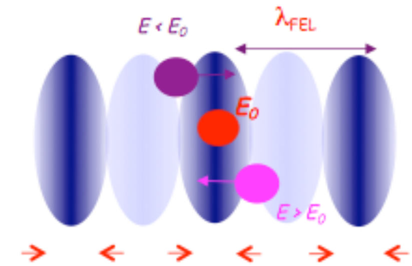
CEC, Example suitable for RHIC

Cooler consists of the modulator section, amplifier (Free Electron Laser), and kicker section. An Energy Recovery Linac (D. Kayran's presentation) will deliver the beam.



$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{\gamma m_e}}$$





$$\phi = \frac{\omega_p l_m}{\gamma c} \approx \frac{\pi}{2}$$

$$c\delta t = -D\frac{\delta\gamma}{\gamma_0}$$

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_p} >> R_{D\parallel,lab} = \frac{c\sigma_{\theta\gamma}}{\gamma^2\omega_p}$$

FEL exponentially increases energy and density modulation in electron beam (FEL Green function). G~10^2-10^3.

Periodic electric field reduces ions energy spread

Potential of CEC

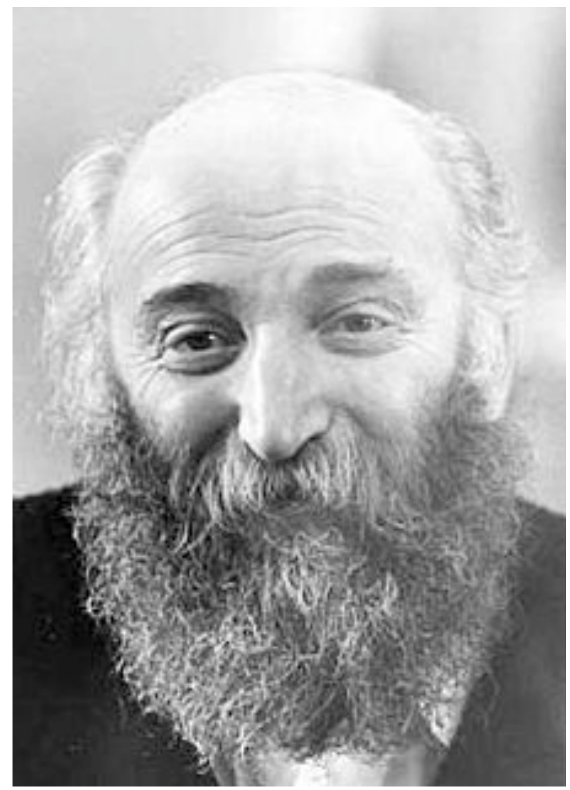
Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	Coherent Electron Cooling, hrs 1D/3D
RHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
RHIC	p	250	~100	40,246 ∞	> 30	0.1/0.3
LHC	p	7,000	~ 1,000	13/26	∞ ∞	0.3/<1

Program	Expected gain
RHIC polarized protons	2
eRHIC	5
LHC	2

Outline

- Why to cool accelerator beams
- Stochastic cooling
- Coherent electron cooling
- **Electron cooling**

Proposed by G. Budker in Novosibirsk in the beginning of the 60's. (Derbenev's doctoral thesis "Theory of electron cooling").



E-cooling process, general description

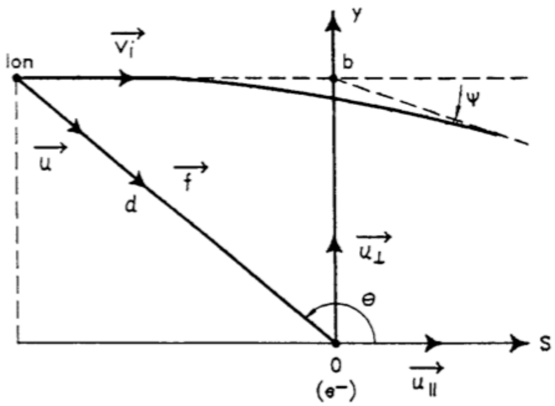
- E-Cooling is thermalization of two component plasma: hot ions, cold electrons. Ions are cooled.

E-cooler typically consists of:

- Source of low emittance electrons (e-gun) and accelerator
- **<u>Ion energy has to be equal to energy of electrons!</u>**
- Cooling section (ions interact with electrons, the section can include magnetic field)
- Electron dump (possibly after deceleration in ERL)
- E-beam is renewed every time ions interact with electrons

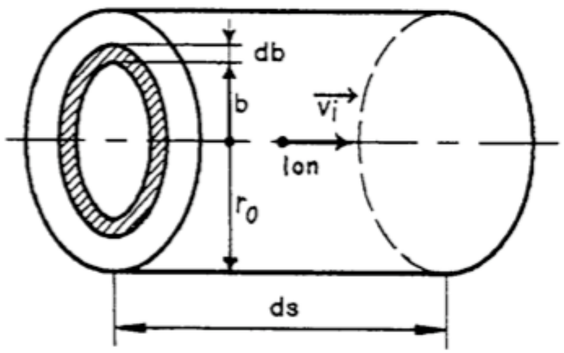
- Because the e-beam is renewed, the ion temperature asymptotically approaches the electron temperature

Friction force and cooling rate (non-magnetized)



1. Energy variation in a single (long-range) collision

$$\Delta E_i = \frac{p_e^2}{2m_e} = \frac{2Z^2e^4}{m_e v_i^2 \rho^2}$$



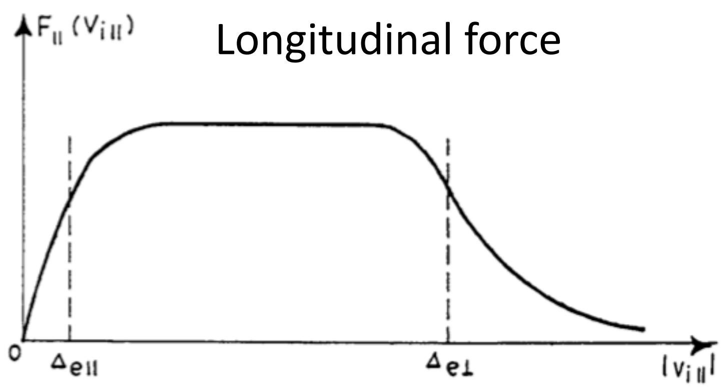
2. Total force is obtained by integration over all ρ's and the electron beam distribution

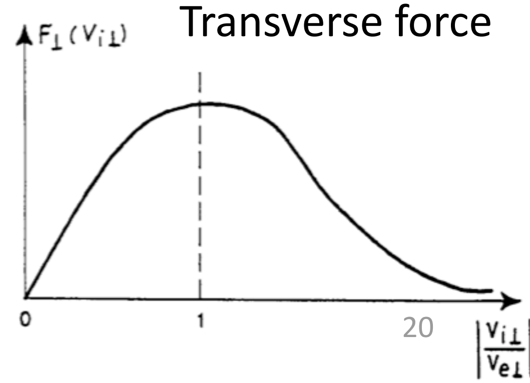
$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e}{m_e} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \int \frac{\vec{v}_i - \vec{v}_e}{\left|\vec{v}_i - \vec{v}_e\right|^3} f(\vec{v}_e) \mathrm{d}^3 v_e$$

3. Friction force and cooling rate

$$\frac{1}{\tau} = -\frac{1}{v_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} = -\frac{F(v_i)}{p_i}$$

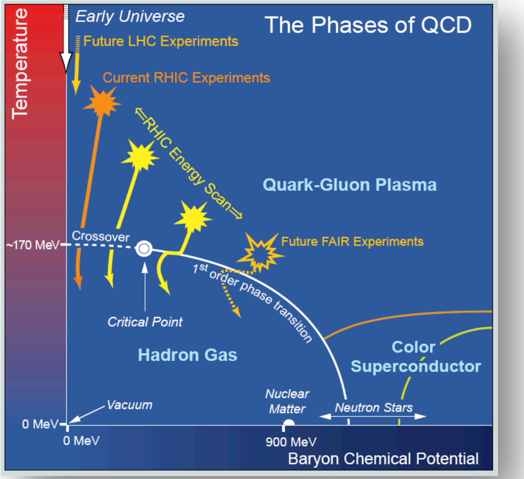
$$\tau_{lab} = \gamma \frac{C}{L_{cool}} \tau$$



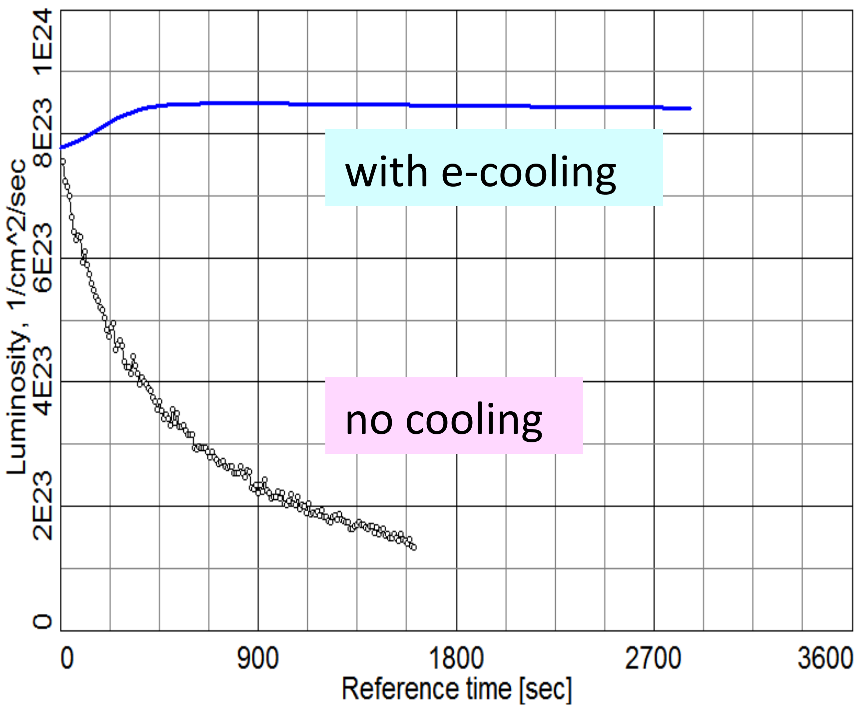


RHIC low (high?) energy electron cooling

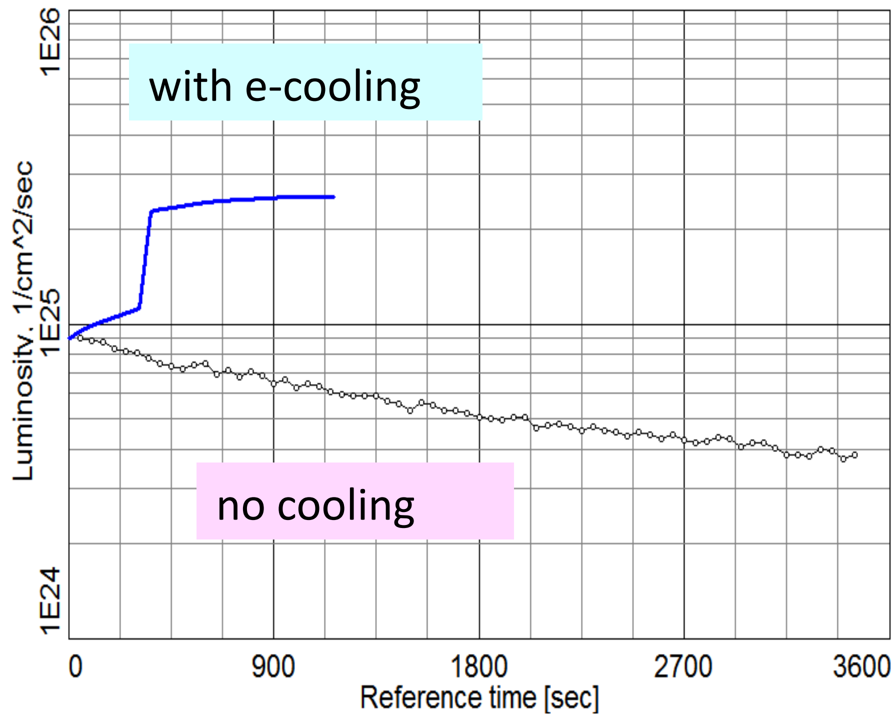
- Factors affecting RHIC performance at low energy
  - Intra-beam scattering
  - Space-Charge
- E-cooling can reduce their effect



γ=2.7, factor of 3 increase of luminosity

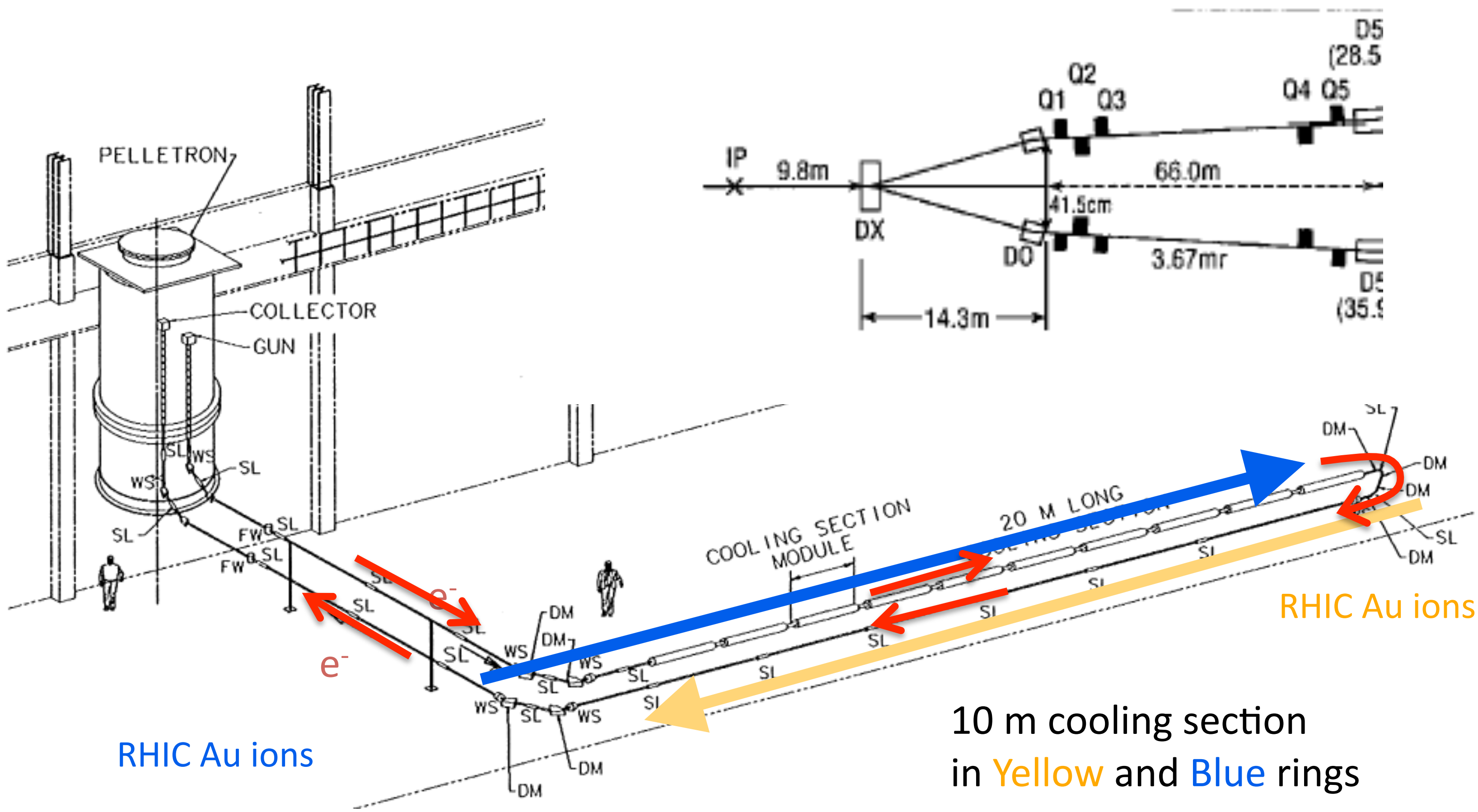


γ=6.6, factor of 6 increase of luminosity



RHIC low (high?) energy electron cooling

- Fermilab cooler can be brought to BNL after Tevatron operations are shut down.
- Peletron high-voltage (5 MV) generator with an e-gun (100 mA) and collector inside
- Recirculation loop with two cooling sections. Charge/energy recovery.
- Installation: 2012. Commissionig and operations: 2013-2014.



This presentation heavily borrows from other presentations

- Stochastic cooling for RHIC: J.(M.) Brennan, M. Blaskiewicz
- Coherent electron cooling: V. Litvinenko
- RHIC Low energy electron cooling: A. Fedotov
- CERN Accelerator School (general description of stochastic and electron cooling)